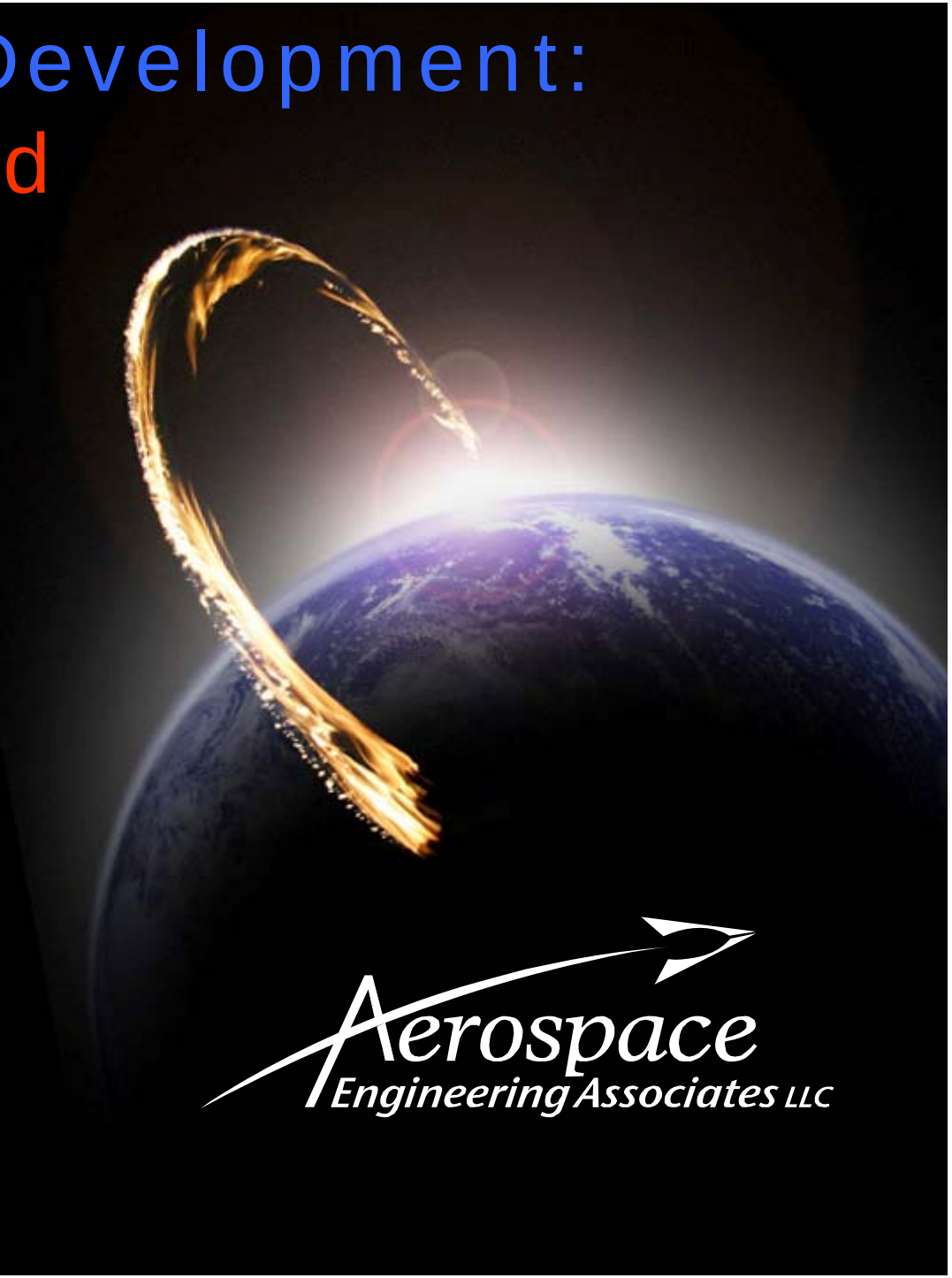
Space System Development: Lessons Learned



Overview

NASA PM CHALLENGE
February 24-25, 2009

Aerospace Engineering Associates LLC

Joe Nieberding

OUTLINE

- Introduction
- Summary of Cases Analyzed
- Selected Sample Cases
- Causation Summary
- Applying the Lessons:
  A Sample Set of Program Principles
- Conclusions

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Introduction

- **Very top level summary of two day presentation developed to assist today's space system developers**
  - Explore overarching fundamental lessons derived from
    - Many specific mishap case histories from multiple programs
    - "Root" causes not unique to times/programs
- **Will cover some material from the two day presentation:**
  - A few of the detailed case histories
  - A summary of causes for all case histories
  - Sample countermeasure "principles"
- **References given for all resource information**
  - Lessons learned charts (yellow background) were either developed independently by AEA or extracted from resource information

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Presenter

Joe Nieberding:

Mr. Nieberding has over 40 years of management and technical experience in leading and participating in NASA independent review teams, and in evaluating NASA advanced space mission planning. Before retiring from NASA GRC in 2000, under his direction numerous studies were conducted during 35 years at GRC to select transportation, propulsion, power, and communications systems for advanced NASA mission applications. His Advanced Space Analysis Division led all exploration advanced concept studies for GRC. In addition, he was a launch team member on over 65 NASA Atlas/Centaur and Titan/Centaur launches, and is a widely recognized expert in launch vehicles and advanced transportation architecture planning for space missions. Mr. Nieberding is co-founder and President of Aerospace Engineering Associates.

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35 Case Histories Covered In The Two Day Presentation

Case	Event	Case	Event	Case	Event
Atlas Centaur F1	Centaur weather shield structural failure	Titan Centaur 6	Degraded Titan Stage 2 engine performance	Titan IVB-32	Loss of Centaur attitude control – spacecraft delivered to useless orbit
Atlas Centaur 5	Atlas booster engine shutdown on pad – vehicle destroyed	Atlas Centaur 43	Atlas thrust section in-flight explosion	GPS IIR-3	On pad rain damage to spacecraft
Apollo 1	Command Module fire	Seasat	Loss of electrical power (L+105 days)	Mars Climate Orbiter	Spacecraft impacted Martian surface
Apollo 13 POGO	Diverging stage 2 POGO – premature engine shutdown	Atlas Centaur 62	Loss of Centaur attitude control due to LOX tank leak	Mars Polar Lander	Uncontrolled descent to Martian surface
Apollo 13 Explosion	Command Module LOX tank explosion	Atlas Centaur 67	Loss of vehicle attitude control following ascent lightning strike	X-33	Program canceled
Atlas Centaur 21	Failure of Nose Fairing to jettison	Galileo	High Gain Antenna failed to deploy	X-43A	Loss of Pegasus attitude control
Atlas Centaur 24	Loss of control at Centaur ignition	Mars Observer	Loss of contact with spacecraft	CONTOUR	Structural failure of spacecraft due to SRM plume heating
N-1	Program cancelled after four flight failures	STS-51/TOS	Orbiter damaged upon TOS separation system Super Zip firing	Helios	Loss of control under turbulent flight conditions
Atlas Centaur Launch Availability	Increased frequency of launch aborts due to upper air winds	Ariane 501	Inertial Reference Systems shutdown during first stage burn – vehicle destroyed	NOAA N Prime	Spacecraft severely damaged in procedure-challenged ground handling
Skylab	Orbital Workshop Micrometeoroid Shield structural failure	Lewis	Loss of attitude control – battery depletion; mission failure	Genesis	Spacecraft parachutes failed to deploy – some data obtained after crash into the earth
Titan Centaur 1	Centaur engines failed to start	SOHO	Loss of attitude control – communication lost for 3 months	DART	Spacecraft hit target; premature depletion of attitude control propellants
Atlas Centaur 33	Loss of Atlas control – booster separation disconnect anomaly	WIRE	Loss of primary instrument cryogens – mission failure	INDICATES THIS CASE INCLUDED IN THIS SUMMARY	

Selected Sample Cases

Titan IVB-32/Milstar

- **Category: Software Design/Systems Engineering**
- **Problem: Titan IVB-32/Milstar Flight Failure (4/30/1999) - vehicle tumbled and placed Milstar in useless orbit**
- **Impact: Loss of mission (>$1.2B)**
- **Why: Flight software error**
  - Human error in entry of roll rate filter constant
    - Correct value of -0.992476 exp(1) entered as -0.992476 exp(0)
    - Resulted in loss of Centaur roll control
  - Human checks failed to detect error
  - Flight software testing performed with default constants
  - Cape personnel noted unusual lack of roll rate response of vehicle (winds and earth rate)
    - Inadequate diligence in follow-up

Source: Titan IVB-32/Milstar-3 Accident Investigation Board Report, USAF Form 711, USAF Mishap Report

Titan IVB-32/Milstar (cont'd)

- **Accident Investigation Board - "The root cause of the mishap was the software development process that allowed a human error to go undetected." The Accident Investigation Board concluded this root cause is the result of several contributing factors:**
  - Software development process
    - Not well defined, documented, or understood by the multiple players
    - Poorly defined for generation/test of rate filter constants
    - Allows single point failures
    - Weakened by consolidation of involved contractors
  - Testing, validation, and verification
    - Filter rate constants not subject to IV&V
    - No formal processes to check filter constants after flight load at CCAFS
    - Inadequate communication precluded correction of observed problem at CCAFS
  - Quality/mission assurance process
    - Neither LMA or USAF software QA functions understood the overall process – this hindered the transition from oversight to insight
    - USAF transition to insight role poorly implemented

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Titan IVB-32/Milstar (concluded)

LESSONS:

- **Software development processes need to be:**
  - **Carefully designed, documented, and understood by the players**
  - **Formal and comprehensive**
  - **Intolerant of single points of failure**
  - **Failsafe**
  - **Audited**
- **Like hardware, software must be tested in flight configuration**
- **Rigorous discipline and appropriate procedures need to be adopted that "stop the action" until unusual/unexpected events are reconciled**

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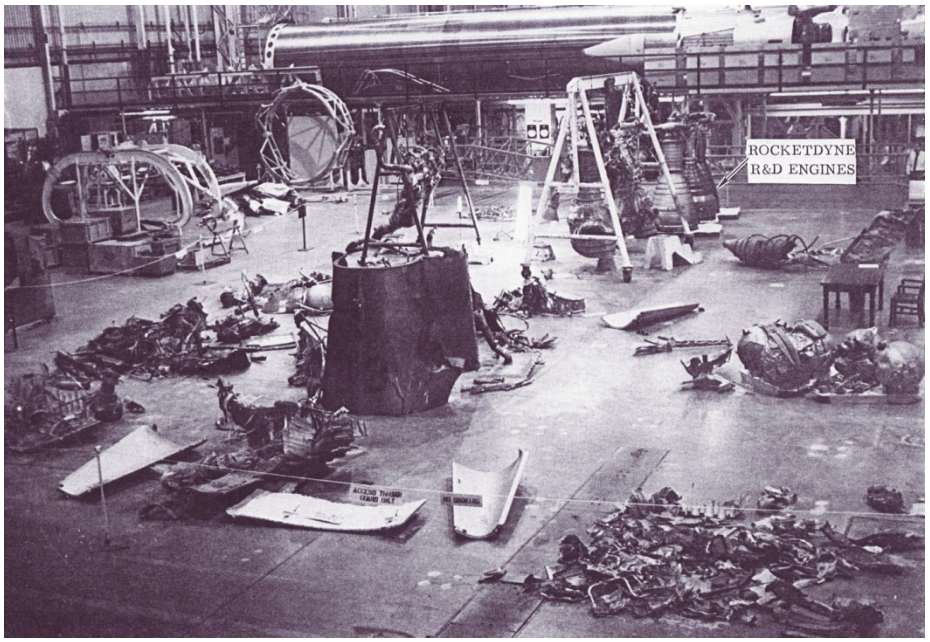
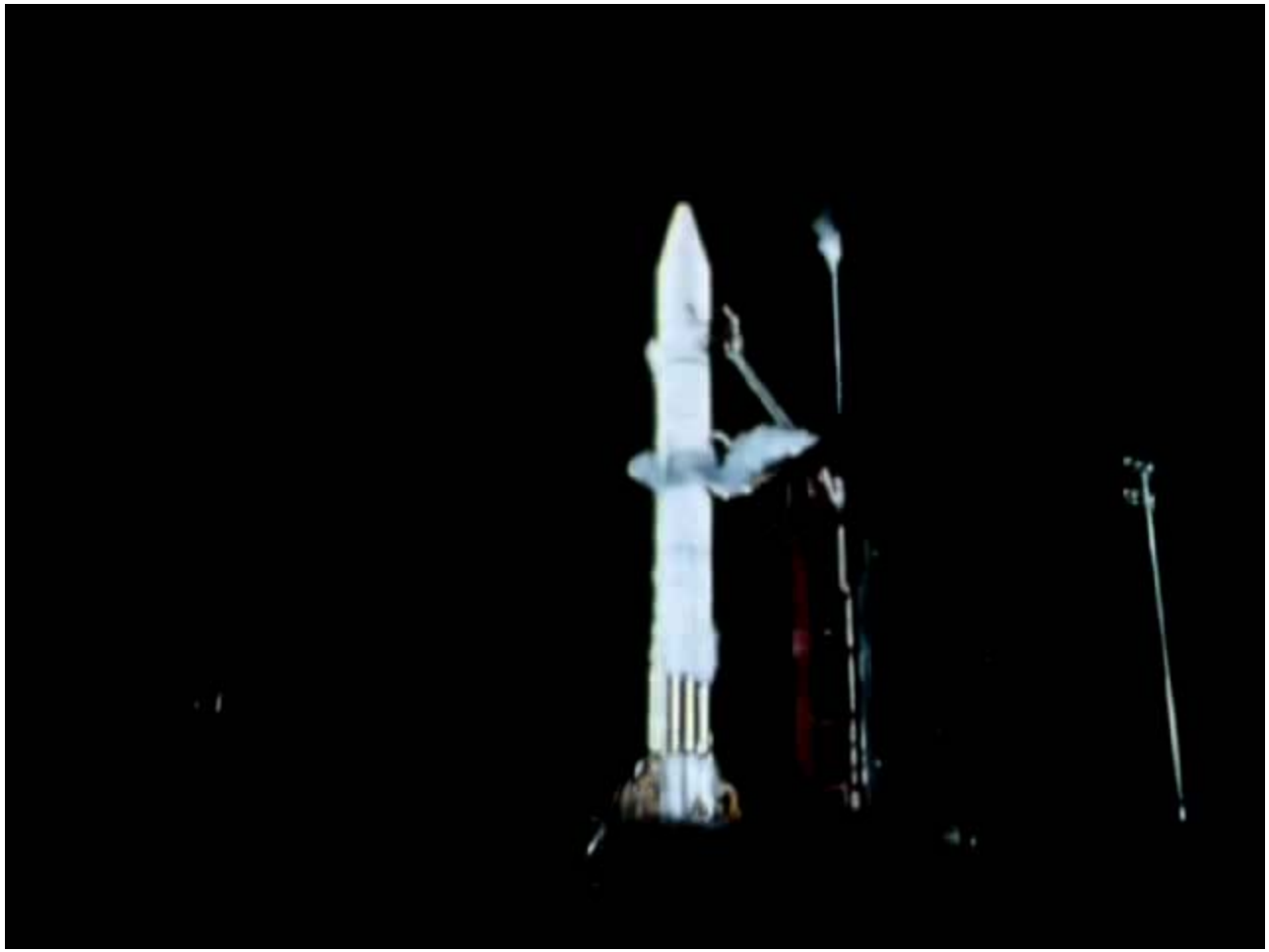
Atlas Centaur A/C-43

- **Category: Production/Operations**
- **Problem: Vehicle destroyed by Range Safety (9/29/1977)**
- **Impact: Loss of Intelsat IVA mission**
- **Why: Explosion in Atlas engine compartment**
  - Atlas engine hot gas leak
  - Hot gas plumbing joint improperly brazed (sensitized) at third tier vendor
    - Resulted in corrosion-induced structural failure
    - Root cause only found after water recovery of hardware

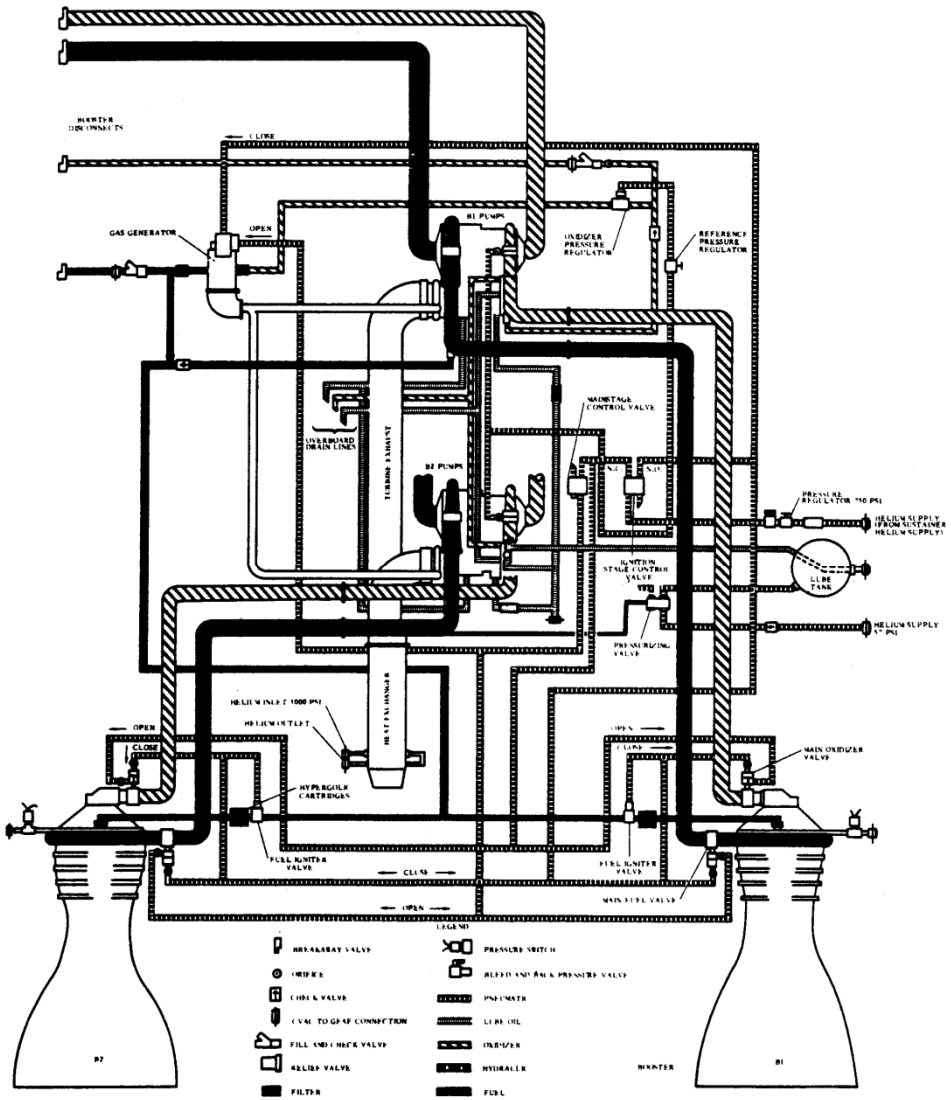


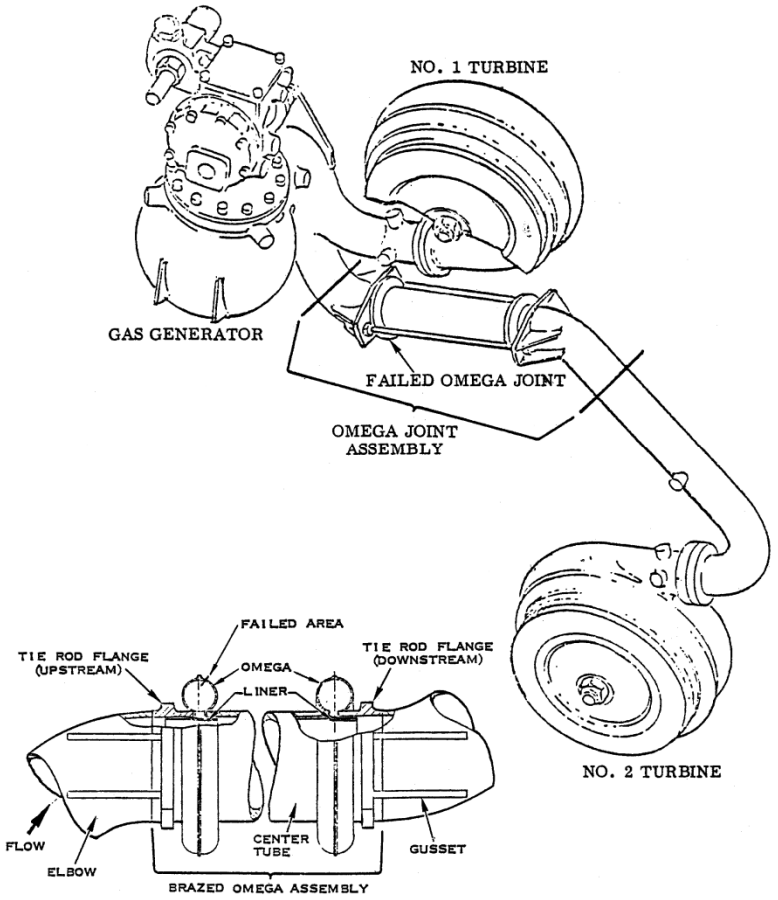
Source: Atlas/Centaur Flight Evaluation Report, AC-43, General Dynamics, March 1978

Atlas Centaur A/C-43 (cont'd) - Video



Atlas Centaur A/C-43 Booster Hot Gas System





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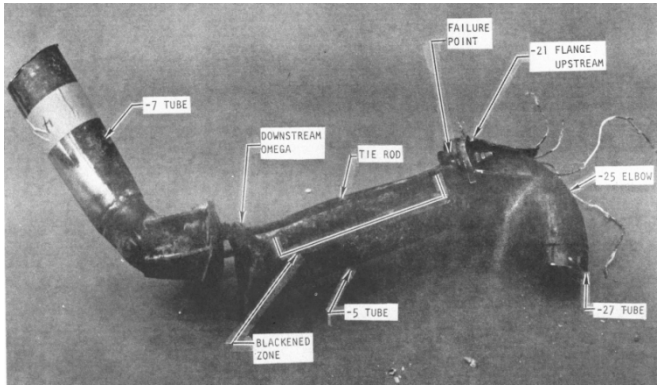
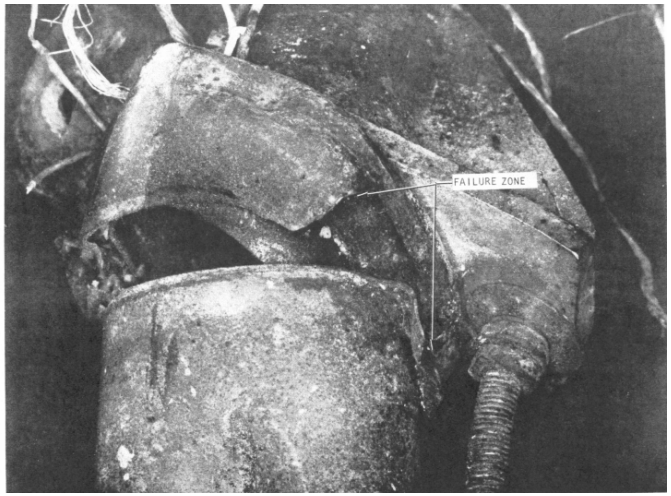
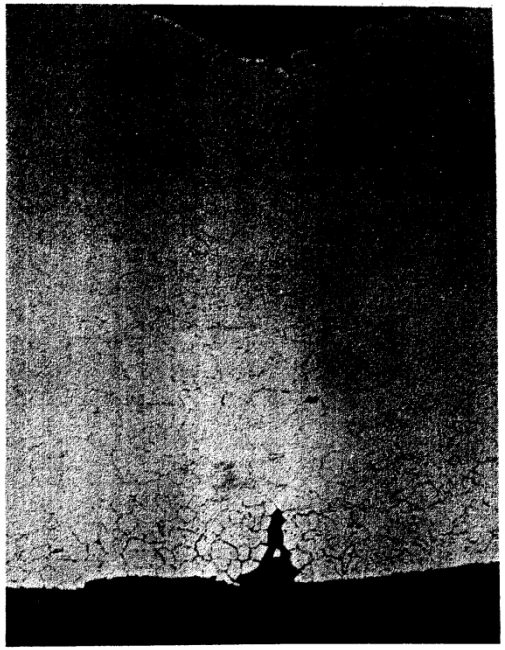
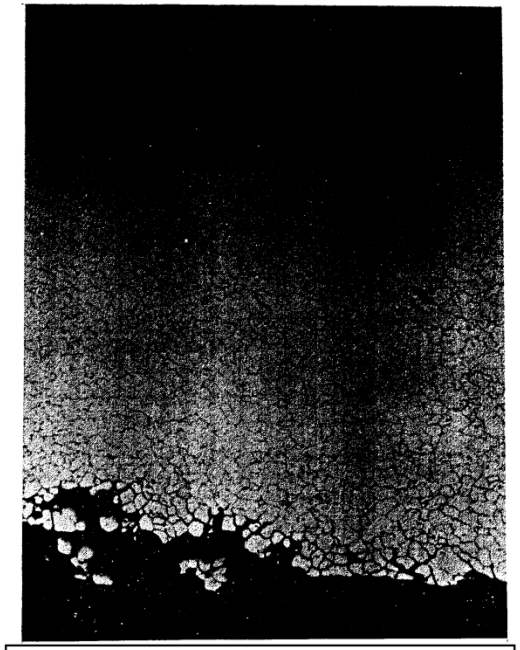
Atlas Centaur A/C-43 Recovered Hardware
Turbine Exhaust Components







Upstream Omega Heat Affected Zone
Unfailed Side
Moderate Intergranular Corrosion & Pitting
200X



Upstream Omega Heat Affected Zone
Failed Side
Severe Intergranular Corrosion
200X

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Atlas Centaur A/C-43 (cont'd)

LESSONS:

- **Components with critical material properties need strict process control, audit, and inspection protocols**
  - **At all tiers**
  - **Specialized experts should be brought in**
- **Have standing process to identify such components (in the design phase) and impose proper controls**

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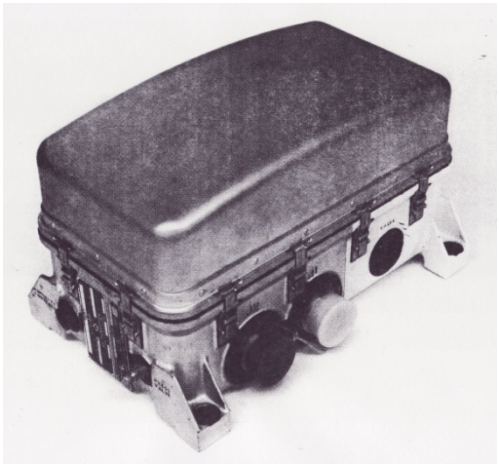
Atlas Centaur AC-24



- **Category: Production/Operations – Systems Engineering**
- **Problem: Loss of vehicle control shortly after Centaur ignition (5/8/1971)**
- **Impact: Loss of first Mariner Mars ’71 mission**
- **Why: Centaur flight control system malfunction**

Source: Mariner Mars ‘71 Mission Atlas/Centaur AC-24 Failure Analysis General Dynamics Report GDCA-BNZ71-018, August 1, 1971

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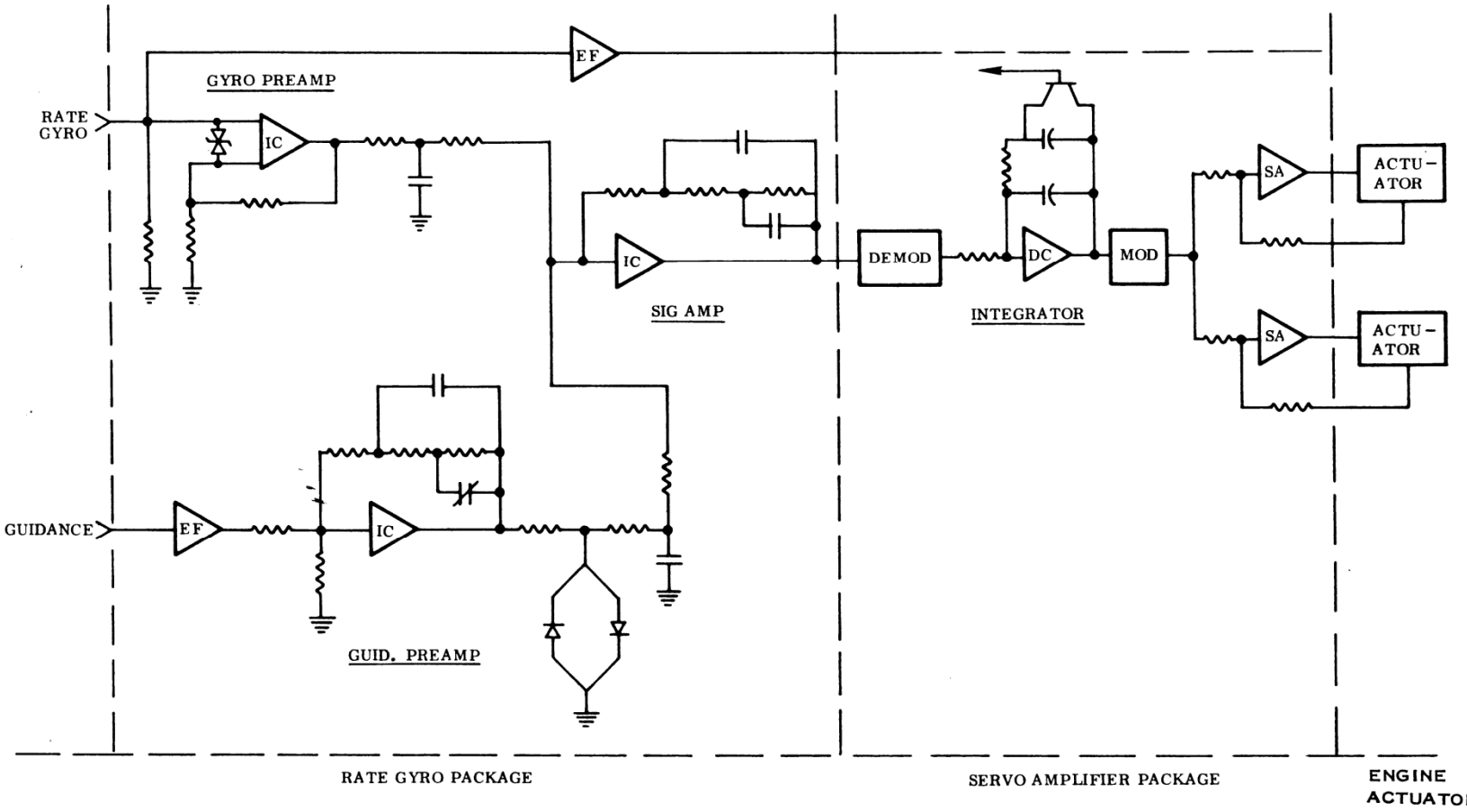
Atlas Centaur AC-24 Centaur Flight Control System Malfunction



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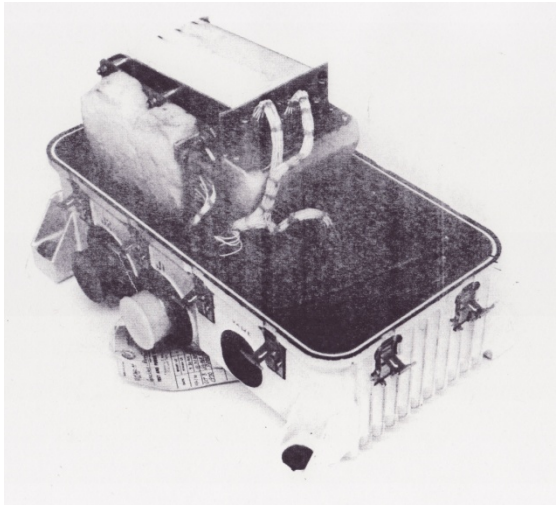
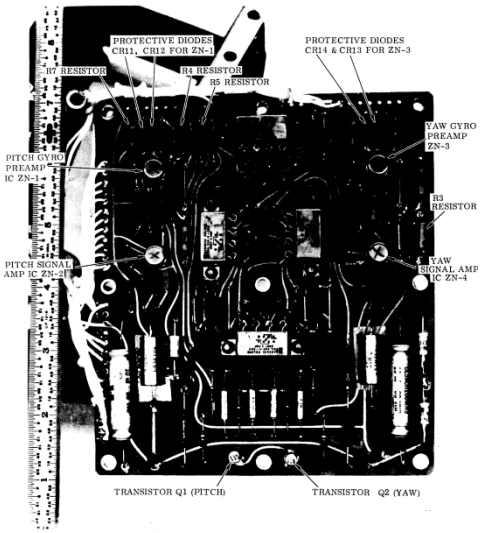
Atlas Centaur AC-24 Centaur Flight Control System Malfunction (concluded)

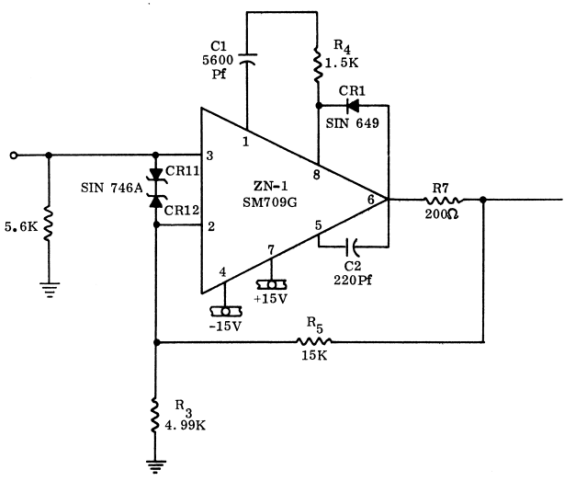
Rate Gyro Unit



Rate Gyro Pitch/Yaw Amplifier Board



Pitch Rate Preamplifier



- **Malfunction occurred in Rate Gyro Unit pitch rate preamplifier**
  - Tests show a latched-up SM709G integrated circuit (IC) matches flight data
  - Zener diodes protect this IC against transient induced latch-up
  - Printed circuit board that flew had ZN-1 and CR11 replaced during rework
  - Box level testing didn't verify Zener functionality
  - Most probable cause: open CR-11 exposed IC to transient induced latch-up
    - CR-11 possibly damaged during installation (foaming) of reworked board into next assembly
    - Subsequent testing would not detect an open CR-11

Atlas Centaur AC-24 (concluded)

- **AC-24 was the only failure of 35 analyzed which was caused by the malfunction of a proper part**

LESSONS:

- **A classic systems engineering lesson:**
  - **Making sure that designs incorporating protective devices include a way to test them at a high enough level of assembly**
  - **And then making sure the tests get done**

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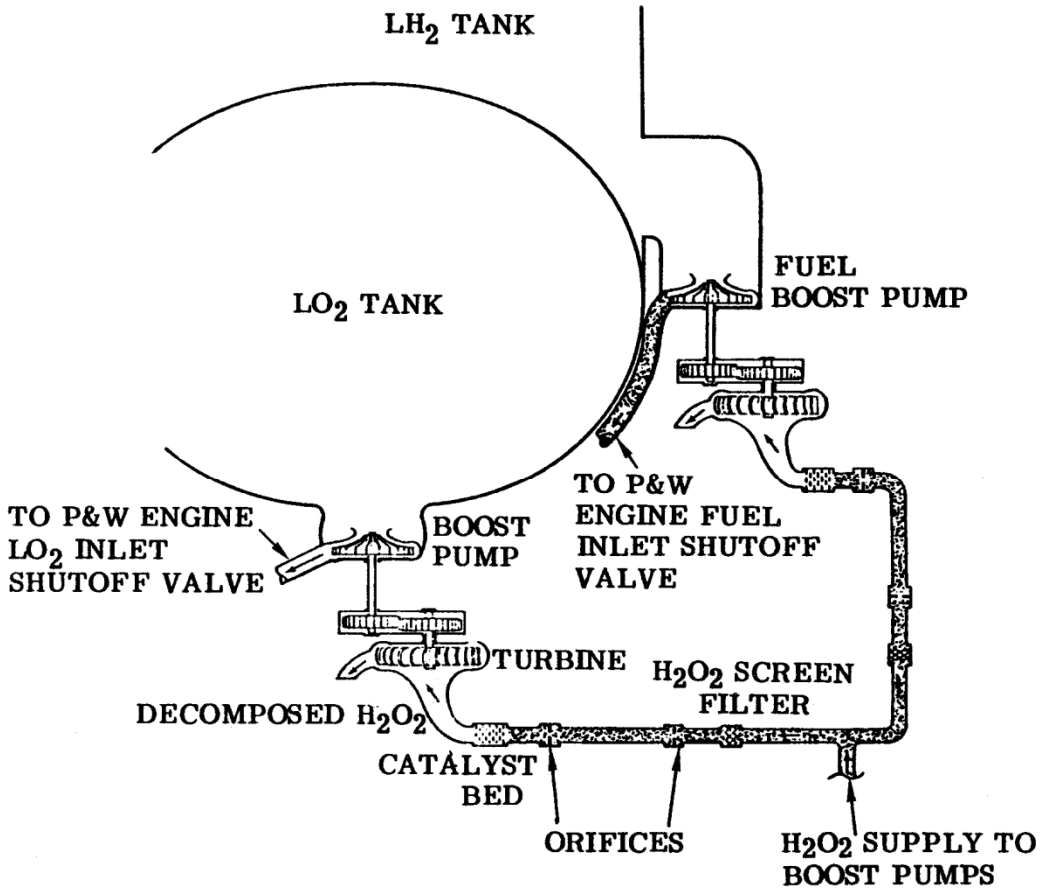
Titan Centaur TC-1

- **Category: Production/Operations – Systems Engineering**
- **Problem: Centaur engines failed to start**
  - First launch of Titan/Centaur (11/2/74)
- **Impact: Loss of Proof Flight mission**
- **Why: Improper start conditions at engine LOX inlets**
  - Probable cause - Centaur LOX boost pump (heritage hardware) locked up due to presence of moisture or foreign object
    - Likely a casualty of a “little old winemaker” situation
  - Prelaunch test judged too complicated

Source: NASA Lewis TM X-71692, Titan/Centaur T/C-1 Post Flight Evaluation report, April 1975

Titan Centaur TC-1 – Centaur Boost Pump Installation



Titan Centaur TC-1 (cont'd)

LESSONS:

- **Pre-launch operational testing of flight systems should be required whenever feasible**
  - **And it should be part of the design requirements to make it feasible**
- **Strive to capture undocumented factory floor "make-it-work" fixes**
- **Sometimes the heritage, not the new system, will fail**
- **Make sure a good FOD system is in place in production facility**

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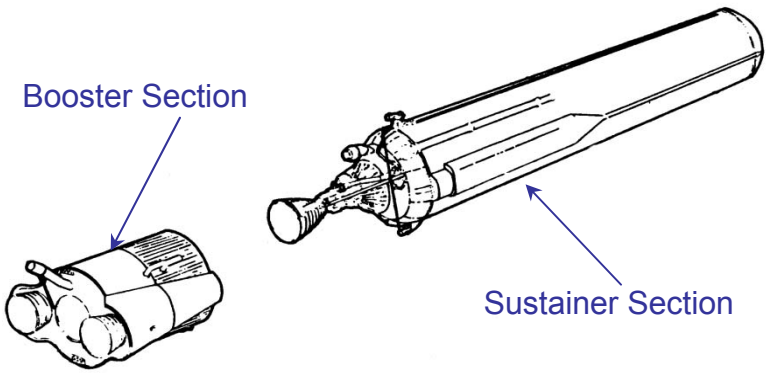
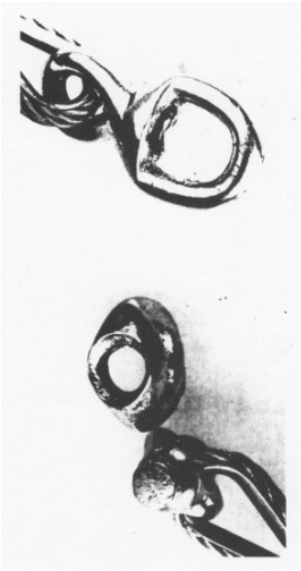
Atlas Centaur A/C-33



Atlas – Stage and a Half Configuration



- **Category: Production/Operations – Program Management**
- **Problem: Vehicle loss of control on ascent (2/20/1975)**
- **Impact: Loss of Intelsat IV mission**
- **Why: Atlas booster staging disconnect failed to separate**
  - Disassembly of swivel in disconnect lanyard

Source: Atlas/Centaur A/C-33 Failure Investigation and Flight Report, Lewis Research Center, December, 1975

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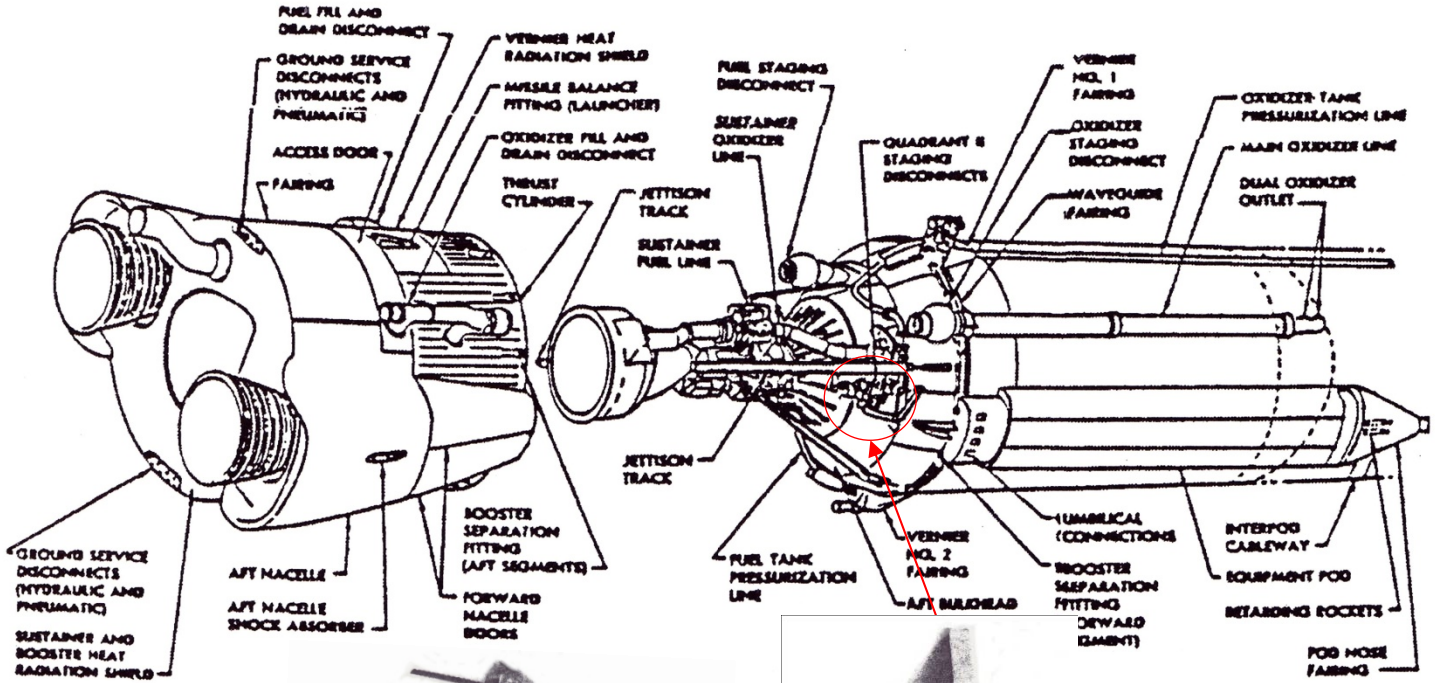
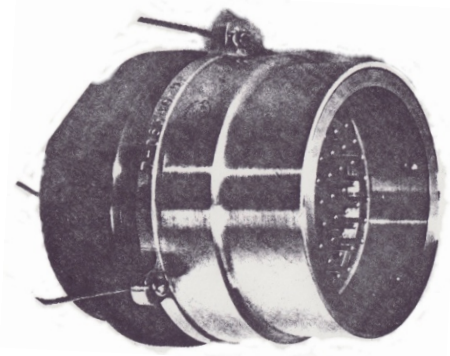
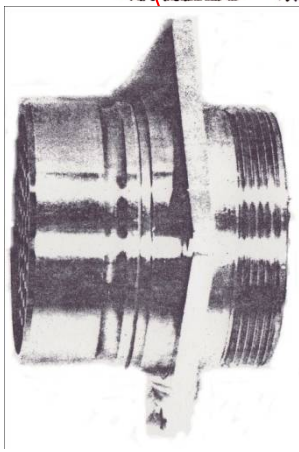
Atlas Centaur A/C-33 Staging Disconnect

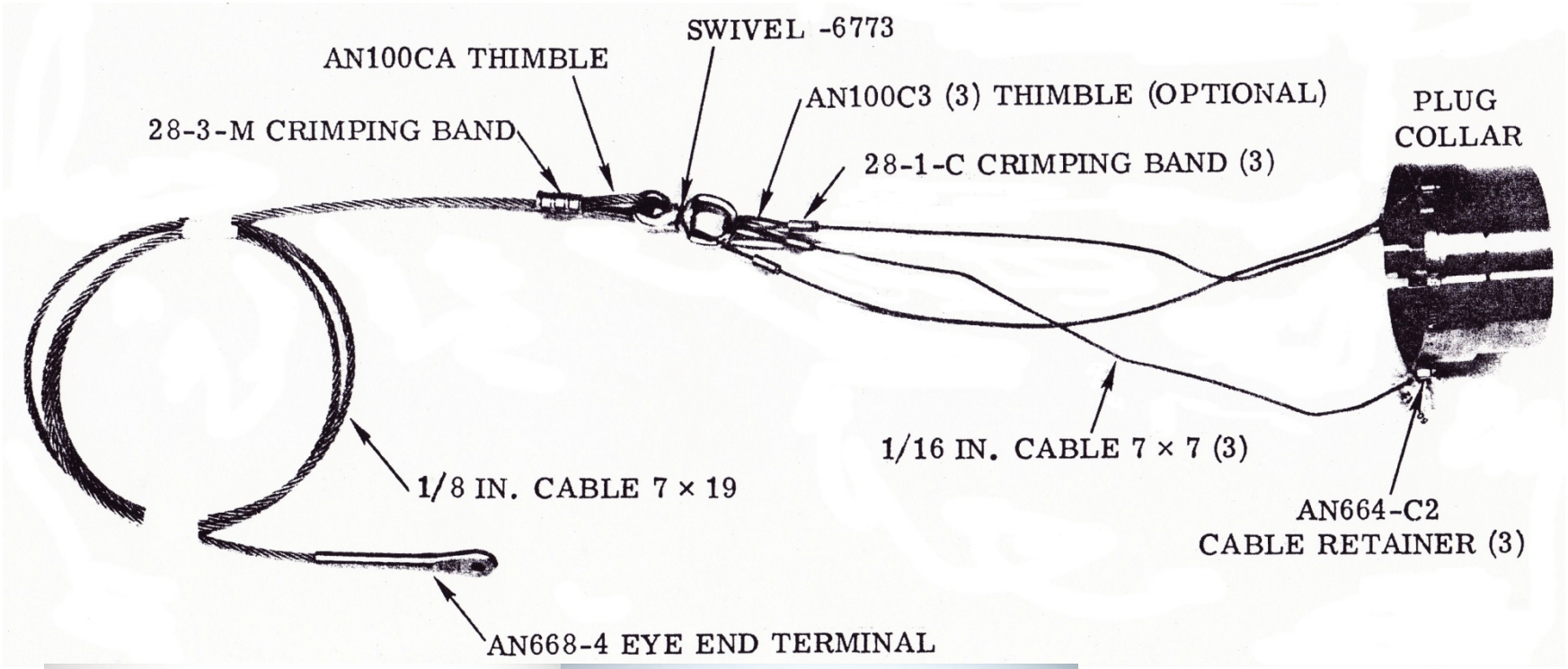






Atlas Booster – Sustainer Staging Disconnect
B600P/J 12

Atlas Centaur A/C-33 Staging Disconnect Lanyard and Swivel



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Atlas Centaur A/C-33 - Observations

- The reliability and quality control systems were indicating swivel failures for nearly eight years, from as early as 1967!
  - Several instances of the swivel's separating into two pieces at the mating face
- It is incomprehensible that effective action was not taken to correct the serious problems with this system and its components
  - The lack of follow-up and urgency suggests that the personnel involved did not understand the disastrous flight consequences that could and did occur when the system malfunctions
  - This was truly an accident waiting to happen!

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Atlas Centaur A/C-33 (concluded)

LESSONS:

- **Adopt an over-arching principle: redundancy is required in flight critical mechanisms**
- **Anything that performs an in-flight actuation should be:**
  - **Treated like a system**
  - **Have a cognizant lead engineer**
- **Unavoidable single points of failure need extra quality attention (e.g. acceptance testing)**
- **A reliable way of flagging and correcting flight critical part quality problems was absent at GD and resulted in this completely preventable loss**
- **Full scale tests are necessary to understand dynamic aspects (e.g. loads) of separation systems**

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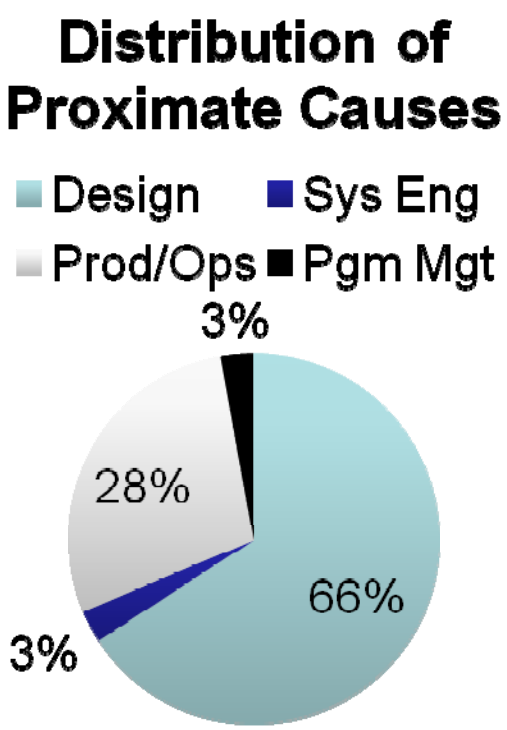
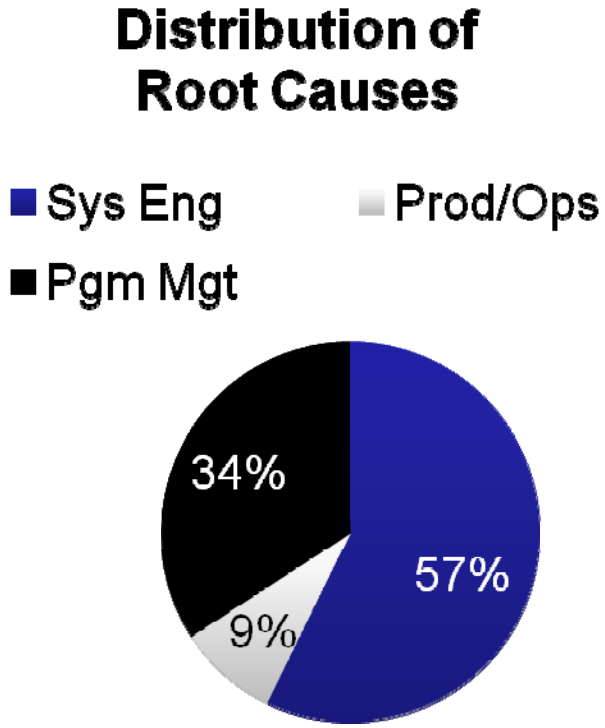
The Engineering Challenge of Electrical Disconnects - Video

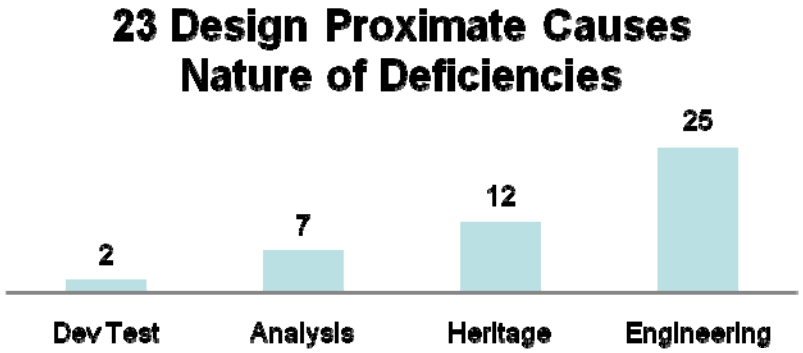
Summary of Causes for the Case Histories Analyzed

(two day presentation cases)

Causation Analysis – Breakdown by Category (35 cases in two day presentation)







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Observations

- **Only one of the 35 mishaps analyzed (Atlas Centaur 24) had failure of a proper part as the cause!**
  - Programs doing good job of acceptance testing
- **Therefore, conventional risk assessment based on piece part failure rates is, at best, incomplete**
- **The other 34 were caused by human error, management weaknesses, systems engineering shortcomings, etc., which are not easily modeled**

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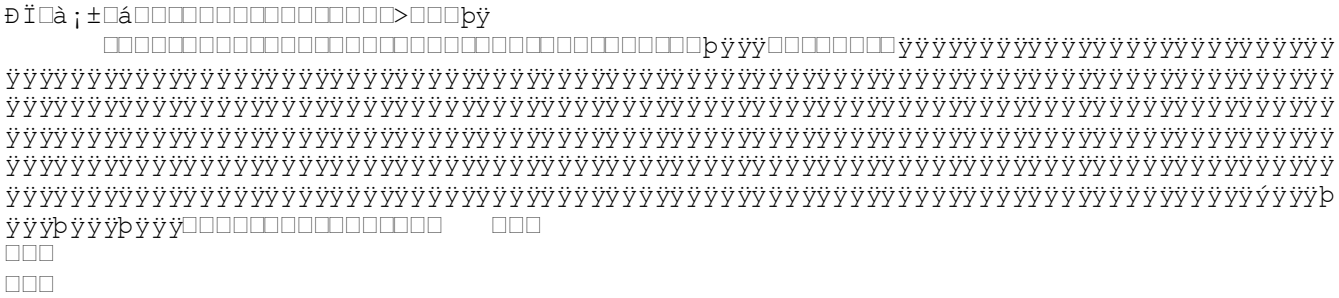
Observations (cont'd)
Some Advance Warning of Mishap in 37% of Cases Analyzed!

Case	Advance Warning	Case	Advance Warning	Case	Advance Warning
Atlas Centaur F1		Titan Centaur 6		GPS IIR-3	
Atlas Centaur 5		Atlas Centaur 43		Mars Polar Lander	Spurious Hall effect sensor output observed in test
Apollo 1		Seasat	Sister program experience with slip ring failures and redesign	Mars Climate Orbiter	Navigation team observation of unexpected trajectory data
Apollo 13 POGO	Multiple prior Saturn V flights experienced POGO	Atlas Centaur 62		X-33	Independent Assessment Team input
Apollo 13 Explosion		Atlas Centaur 67	Field mill activity; ambiguous balloon data	X-43A	
Atlas Centaur 21		Galileo		CONTOUR	
Atlas Centaur 24		STS-51/TOS		Helios	
N-1	Inability to achieve successful flight	Ariane 501		NOAA N Prime	Significant history of recurring poor factory discipline
Atlas Centaur Launch Availability	Increasing frequency of launch aborts due to upper air winds	Lewis		X-43C	
Skylab		SOHO		Genesis	
Titan Centaur 1		WIRE	Failed functional test	DART	Expert input
Atlas Centaur 33	Multiple prior swivel failures; vendor warning	Titan IV-B-32	Anomalous vehicle roll response while on-stand		

Observations (cont'd):
Testing Deficiencies Had a Pivotal Role in 20 of 35 Cases



Observations (concluded)

- **Programs that adopt a zero-based approach to testing are betting on the ability of the engineering community to foresee all aspects of system performance under all conditions**
  - This is a very risky bet
  - History demonstrates that tests frequently, if not usually, produce unexpected (and unwanted) results

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Applying the Lessons:
A Sample Set of Program Principles

Applying the Lessons:
A Sample Set of Program Principles

- **<u>Issue:</u> Many lessons learned have common themes. The issue is to systematically infuse this knowledge into programs so they're not lessons forgotten**
- **<u>One approach:</u> For large and complex programs, impose a Program specific set of overarching "Principles" that govern how certain things are to be done (i.e. to codify some of the lessons)**
  - Any deviation from these Principles would be cause for special attention (risk management) by Program Management
  - These *ad hoc* Principles would not take the place of existing design standards or similar tools, but rather provide an additional mechanism to flag when special action is warranted

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Applying the Lessons:
A Sample Set of Program Principles (cont'd)

- **Design Review:** **(Causal in 27 of 35 cases)**
  - The acceptability of new designs will be established through a formal design review process staffed by independent peer practitioners of the designers seeking design approval. The reviewers will constitute a design "jury" to determine if:
    - The design will perform as required.
    - The test plan is adequate (development, qualification and acceptance).
    - The test results are successful.
    - The risk management analysis and mitigation plan are sound.
    - The in-flight performance is successful.

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Applying the Lessons:
A Sample Set of Program Principles (cont'd)

- **Testing Program Definition: (Seasat, AC-62, STS-51/TOS, TC-1, AC-24, N1, Ariane 501, SOHO, Titan IVB-32, Mars Climate Orbiter, Genesis, DART)**
  - As a core principle, the flight worthiness of system designs (hardware and software) must be validated through ground testing unless such testing is clearly infeasible – the prevailing rule is that if "it" can be meaningfully tested on the ground, it will be.
  - The following rules apply:
    - Testing will be at highest level of assembly feasible under expected flight environments plus appropriate margins.
    - Designs will permit functional testing as close to launch as feasible.
    - Tests will demonstrate compliance with functional design requirements, *vs.* verifying "built-to-print".
    - Waivers require enhanced margins, redundancy, and robustness of the test program for assemblies making up the design.

Applying the Lessons:
A Sample Set of Program Principles (cont'd)

- **Mechanisms:** (Skylab, AC-21, AC-33, Galileo, STS51/TOS, Mars Polar Lander, Genesis)
  - Collections of components, assemblies, mechanisms, and subsystems that must affect an in-flight separation, deployment, or articulation will be designated a "system" and be placed under the cognizance of a lead engineer who will be responsible for all aspects of its design, development, production, test and in-flight performance.
    - These systems will incorporate a redundant separation, deployment or articulation capability and,
    - Will be qualified for flight through functional testing under the appropriate environments.
- **Critical Materials:** (AC-43)
  - Components used in applications for which the material properties are critical for proper operation will be subject to an enhanced inspection and acceptance process involving appropriate experts.

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Applying the Lessons:
A Sample Set of Program Principles (cont'd)

- **Analytical Modeling:** **(Causal in 12 of 35 cases)**
  - All analytical modeling on which designs are based will be test-validated and acquired from at least two independent sources.
  - A plume heating analysis is required of all systems employing a new propulsion arrangement.
- **Software:** **(Causal in 6 of 35 cases)**
- All software development, testing, and application processes will be controlled by a single, formal, and configuration managed Software Management Plan for which a single individual is responsible.
- Proper operation of flight software will be demonstrated in pre-flight functional testing of flight hardware to the greatest extent possible.
- Exceptions must be individually waived.

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Applying the Lessons:
A Sample Set of Program Principles (cont'd)

- **Heritage Items: (Contributing cause in 12 of 35 cases)**
  - Any item adopted for use based on successful flight performance in another program will be deemed unqualified in the adopting application until a thorough analysis has been performed to confirm that the adopting application is identical (or less demanding) in all relevant features to the prior successful application.
  - Any deviations must be qualified by test.

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Applying the Lessons:
A Sample Set of Program Principles (concluded)

- **Advance Warning:** **(Causal in 13 of 35 cases)**
- An effective system for facilitating communication between those concerned about a potential safety-of-flight problem and those in a position to reconcile it is to be designed and embedded in the Program culture (easier said than done - but surely it's doable!). It must be:
- Formal and visible.
- Reliable (if not foolproof).
- Simple to use with quick feedback.
- Plugged into real authority to stop the action.
- Culturally valued and respected.
- **Etc.**

Applying Appropriate Principles:
•It's never too late to start
•Applying some is better than applying none

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Conclusions

Conclusions
(Based on analysis of all cases in two day presentation)

- **Most mishaps can be broadly attributed to:**
  - Ineffective systems engineering
  - Bad design engineering (hardware and software)
  - Inaccurate results of analyses, simulation, and modeling efforts
  - Ineffective management (including misapplied “themes” – e.g. Better Faster Cheaper)
  - Non-existent or inadequate process verification and enforcement (software and hardware)
  - Inadequate or improper testing and verification (software and hardware)

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Conclusions (cont'd)

- **Most mishaps can be broadly attributed to (cont'd):**
  - Failure to understand software "failure" mechanisms
  - Ineffective communication processes
  - Unwarranted reliance on heritage and similarity
  - Flawed failure analyses
  - Undetected common causes
  - Weaknesses in technical leadership (the "human element")

- **Quality in all the above areas is essential for mission success**
- **Over decades, the same root causes appear repeatedly**
  - **There are few new ones!**

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Conclusions (cont'd)

Why?

- **The lessons are largely the property of those in close proximity to the "incident" (who do benefit)**
  - With time, the keepers disappear
  - What's left is a diminishing, second-hand memory that also fades quickly
  - Paper, or even electronic, systems are, by themselves, insufficient to keep the memory alive
    - Lack the live element to reveal the nuances and convey the passion
      - And fill in the details the official "record" omits
    - Accessed by specific subject matter of interest
      - Reactive - you have to know what to search for
      - Ill-suited to be proactive – i.e., convey wide range of over-arching lessons learned "truths"
- **Basically, there is no universal, regular, methodical, and satisfying approach to exploiting lessons learned**
  - What's done is pretty much catch as catch can

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Conclusions (concluded)

- **Organizations desiring to profit from applying lessons previously learned should develop their own tailored approaches**
- **Should be part of the Program Plan and include consideration of approaches such as:**
  - Adopting and enforcing a set of Program Principles
  - Presenting case histories/lessons learned on a regular basis
  - Arranging seminars with the “keepers” (aka greybeards)
  - Providing mentors on an on-going basis for specific needs
  - Offering incident-based training courses
  - Conducting independent reviews by experienced subject matter experts

The business of transferring lessons learned is best done as a “contact sport”

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Glossary of Terms

Acronym	Definition	Acronym	Definition
ACS	Attitude Control System	GPS	Global Positioning System
ACTS	Advanced Communications Technology Satellite	GN&C	Guidance Navigation and Control
AEA	Aerospace Engineering Associates	I&T	Integration and Test
ADDJUST	Automatic Determination and Dissemination of Just Updated Steering Terms	IC	Integrated Circuit
APL	Applied Physics Laboratory	IIP	Instantaneous Impact Point
APU	Auxiliary Power Unit	IPAO	Independent Program Assessment Office
ATK	Alliant Techsystems	IRU	Inertial Reference Unit
BFC	Better Faster Cheaper	ISA	Initial Sun Acquisition (SOHO)
CAIB	Columbia Accident Investigation Board	ISSP	International Space Station Program
ESR	Emergency Sun Reacquisition (SOHO)	IV&V	Independent Verification and Validation
FOD	Foreign Object Damage	JPL	Jet Propulsion Laboratory
GAO	Government Accountability Office	JSC	Johnson Space Center
GD	General Dynamics	KSC	Kennedy Space Center

Glossary of Terms

Acronym	Definition	Acronym	Definition
LCCE	Life Cycle Cost Estimate	NASA	National Aeronautics and Space Administration
LM	Lockheed Martin	NOAA	National Oceanic & Atmospheric Administration
LOX	Liquid Oxygen	NRA	NASA Research Announcement
LMA	Lockheed Martin Astronautics	NTO	Nitrogen Tetroxide (N_2H_4)
LSP	Launch Service Provider	OSP	Orbital Space Plane
MDCA	Microgravity Droplet Combustion Apparatus	P&W	Pratt and Whitney
MES	Main Engine Start (Centaur)	PDT	Product Development Team
MMH	Monomethylhydrazine	POGO	Longitudinal oscillation (as in POGO stick – not an acronym)
MO	Mars Observer	RLV	Reusable Launch Vehicle
MOU	Memorandum of Understanding	RSRM	Redesigned Solid Rocket Motor
MS	Meteoroid Shield	S&MA	Safety and Mission Assurance
MSFC	Marshall Space Flight Center	S/C	Spacecraft
NAC	NASA Advisory Council	SAIC	Science Applications International Corporation

Glossary of Terms

Acronym	Definition	Acronym	Definition
SDR	System Design Review	UAV	Uncrewed Aerial Vehicle
SE	Systems Engineering	USAF	United States Air Force
SEB	Source Evaluation Board	VSE	Vision for Space Exploration
SLI	Space Launch Initiative		
SOA	State of the Art		
SOX	Solid Oxygen		
SRB	Solid Rocket Booster		
SRM	Solid Rocket Motor		
SRR	System Requirements Review		
SSME	Space Shuttle Main Engine		
SSTO	Single Stage to Orbit		
STS	Space Transportation System		
TOS	Transfer Orbit Stage		

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MISSION

AEA's mission is to leverage the vital lessons learned by NASA's spacefaring pioneers to strengthen the skills of today's aerospace explorers.